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Videokeratoscope Accuracy and its Potential Use in Corneal Optics Research

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An investigation was conducted to determine if the EyeSys Corneal Analysis System could measure the topographic elevation of cornea-like test surfaces accurately enough to permit detailed studies of corneal optics. For this purpose, elevation measurement accuracy should be better than 1.0 µm. Six rotationally symmetric apheric test surfaces were measured to assess instrument accuracy. Our results showed the EyeSys system was not able to achieve this level of accuracy for any of the test surfaces. Depending on the surface, accuracies expressed as RMS or 12th ring errors were in the 2 to 9 and -2 to -6-µm ranges, respectively.

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Preface

LTC Salmon, U.S. Army Reserve, is an Assistant Professor of Optometry at Northeastern State University, Tahlequah, Oklahoma. He is completing a PhD in visual sciences and physiological optics at Indiana University, Bloomington, IN.

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Introduction

Approximately half of the world's population have refractive errors significant enough to require correction (International Society of Refractive Surgery, 1997). Grosvenor (1976) estimated that for the age group of 18-30-year old males, 30-35 percent wear spectacles. Walsh (1989) reported that 33 percent of entry-level Army infantry wore spectacles; less than 1 percent wore contact lenses. Spectacles and contact lenses are the most commonly used methods for correcting refractive errors, but for nearly a century physicians have been exploring surgical methods to achieve the same end. In the last 10 years, refractive surgery has become an increasingly popular alternative to spectacles and contact lenses. These surgical techniques are designed to alter the shape of the anterior corneal surface and thus induce a change in the eye's optical properties. The cornea is the clear front surface of the eye which works in conjunction with the pupil and lens to form an image on the retina (Figure 1). Among the elements of the eye's optical system, the anterior surface of the cornea alone accounts for approximately 75 percent of the eye's refractive power and is therefore the single most important optical surface in the eye. It is also the most easily accessible for examination and modification.

Refractive surgery can be used to correct myopia (nearsightedness), hyperopia (farsightedness), and astigmatism. Myopia occurs when the eye's optics form a clearly focused image in front of the retina, and the image which actually falls on the retina is blurred. This may be corrected by flattening the central cornea, shifting the focus backwards towards the retina. In hyperopia, the clearly focused image is formed beyond the retina, and again the image which actually falls on the retina is blurred. This may be corrected by flattening the peripheral cornea and shifting the focus forward. Astigmatism is a more complicated form of optical defocus which can be mitigated by flattening only certain zones of the cornea.

Both incisional and photo-ablative techniques are used to surgically reshape the cornea in order to correct refractive errors. The two most widely used incisional procedures are radial keratotomy (RK) and astigmatic keratotomy (AK). In RK, the surgeon makes a series of four to eight radial micro-incisions in the mid-periphery of the cornea, while the central zone is spared (Figure 2a). The equally spaced incisions are made to a depth of approximately 90 percent of the cornea thickness, and this causes the central zone of the cornea to flatten. This provides correction for mild levels of myopia. AK is used to correct astigmatism, and it involves micro-incisions made concentrically along the periphery of cornea in the region where the steepest corneal slope exists (Figure 2b). The steepest regions of the cornea are flattened, and this can correct moderately high levels of astigmatism.

PRK (photo-refractive keratectomy) and LASIK (laser assisted in-situ keratomilieusis) are photo-ablative procedures which use an excimer laser to vaporize selected regions of the cornea. Currently, PRK is perhaps the most popular refractive surgery method, but among some surgeons, LASIK is becoming the treatment of choice. In PRK, the doctor scrapes off the upper

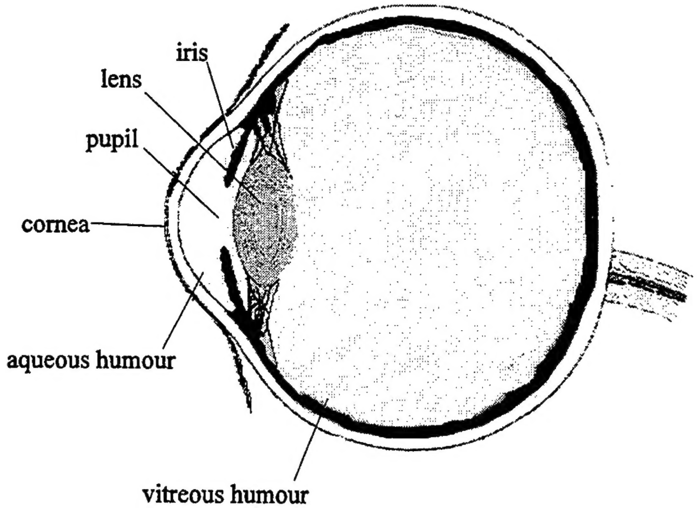


Figure 1. A side view of the human eye.

layer of the corneal cells (epithelium) and exposes the underlying stroma to the laser beam, which vaporizes portions of the tissue to "sculpt" the cornea into a new shape. The central cornea is more strongly ablated in myopia, while in hyperopia, peripheral regions are more strongly ablated. Astigmatic correction is also possible. LASIK is a variant of PRK which has been nicknamed the "flap and zap" technique. A motorized blade known as a microkeratome slices through the upper portion of the cornea creating a round flap which is pulled back to expose the interior stroma (Figure 2c). As in PRK, the excimer laser then ablates stromal tissue to a pre-computed depth, and the flap is replaced (Taylor et al., 1989) to cover the ablated portion of the cornea.

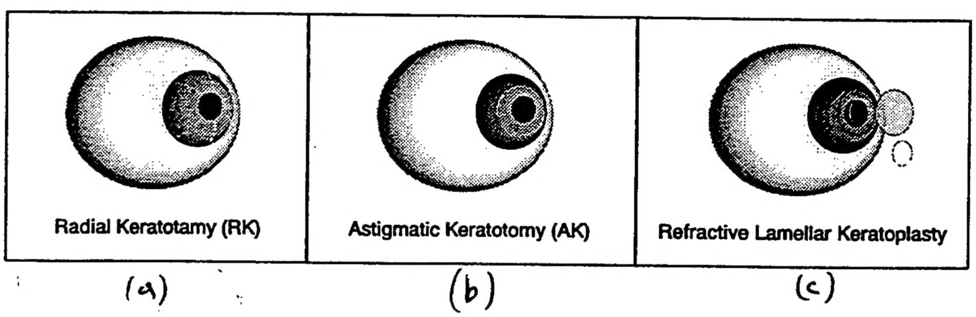


Figure 2. a) Radial incisions with radial keratotomy, b) concentric incisions with astigmatic keratotomy, and c) flap in the anterior similar to that used in LASIK.

A completely different approach, which is currently investigational in the U.S., indirectly changes central corneal shape by implanting small precision plastic bands in the mid-peripheral zone (Burris et al, 1993; Nagy et al, 1997). These thin, transparent half-rings are inserted at mid-depth within the cornea. The central cornea flattens due to the anterior bulging of the periphery of the cornea, and this provides correction for myopia. The "intrastromal corneal ring" technique has been in general use in Europe since 1996.

Surgical correction of refractive error is appealing for both cosmetic and logistical reasons. Glasses and contact lenses are often considered unattractive, inconvenient, or uncomfortable. Proponents of refractive surgery have argued that over the long term it may be more cost effective than contact lenses. These arguments, however, do not take into account the risks and complications associated with the surgery. These include light sensitivity, haze, glare, starbursting, induced astigmatism, and uncorrectable optical artifacts. These potential problems may be ignored when the impetus to correct the refractive error is high, as in young individuals seeking to become aviators. Almost always the visual success of the refractive surgery is measured by the familiar, though limited, metric of Snellen acuity, which may fail to detect degraded vision and complicated optical aberrations. For example, patients may be able to read the 20/20 line on a Snellen letter chart, but have such poor night vision that they can no longer drive at night (Halliday, 1995).

For some individuals preparing to become military aviators, an uncorrected refractive error may be their only obstacle, and in fact, failure to meet vision requirements is a major cause of disqualification. For male U.S. Army flight school candidates for the period January 1987 to December 1996, 11.5 percent (n = 35,138) failed to meet entry level vision standards (Shannon, 1998). And, this issue is not gender specific. For women, the Canadian Forces reported that for the period 1977-1988, 11.5 percent (n = 477) failed to meet entry level vision standards; and the Belgian Armed forces reported that for the period 1983-1989, 31.0 percent (n = 74) were disqualified due to inadequate visual acuity (Vancutsem and Vandenbosch, 1990). For female U.S. Army flight school candidates for the period 1987-1990, 11.2 percent (n = 774) failed to meet entry level vision standards (Mason, 1995).

To correct vision and to gain entry into flight training, highly motivated candidates may be tempted to undergo one of the available refractive surgery techniques. However, even if the refractive surgeries are successful and free of complications, its long term effects and potential problems are not fully understood. Aviator training is a costly and time intensive process. The cost of training an Army aviator ranges from $225,000 to more than $1,000,000, depending on type of aircraft. The loss of an aviator at any point in his/her expected flight career due to medical problems resulting from refractive surgery is an undesirable event.

Warrant officer candidates seeking entry into Army aviation flight training are required to have an uncorrected Snellen visual acuity of at least 20/20 in each eye and a minimal refractive error (-0.25 to +1.75 diopters (D)) (Rabin, 1996; Walsh and Levine, 1987); commissioned officers are allowed a refractive error of -0.75 to +2.25 D. The use of spectacles to correct refractive error generally is not acceptable in the military aviation environment for various

reasons such as fogging, or the reduced field of view with image intensifier tubes or helmet-mounted displays caused by the spectacle-eye vertex distance. Current Army selection policy rejects candidates who have had refractive surgery, but as previously mentioned, the prospect of overcoming a refractive error to gain entry into flight school can motivate certain individuals to surreptitiously undergo such surgeries. Case histories exist where aviator candidates with disqualifying refractive errors have attempted to circumvent vision standards. Mason (1996) reports an Army aviator student in the preflight training phase who was discovered to have had contact lens "skid marks" on his corneas. Upon investigation, it was learned that the student had been wearing hard contacts lenses in an attempt to modify the shape of his corneas. A search of the U.S. Army Aviation Epidemiology Data Register, a family of databases storing medical history and physical parameters of U.S. Army student and trained aviators, for the period 1982-1998 found 34 cases where entry level students were identified as having undergone RK or PRK, and six trained aviators were identified as having undergone one of these surgeries.

While the corneal scars resulting from RK and AK are relatively easy for a doctor to see, the newer techniques of PRK and LASIK are more difficult to detect. In some cases, PRK or LASIK can be detected by the presence of excessive corneal haze, however, this is not always present. Figure 3 shows two views of the right eye of a 23-year old female who has undergone PRK. Figure 3 (left) shows the eye under low magnification with no sign of the PRK, and Figure 3 (right) shows a magnified slit lamp view of the same cornea, again with no indication of PRK.

Computerized corneal topographers are new clinical instruments which greatly simplify the task of diagnosing subtle corneal surface anomalies, and, clearly, these instruments also can help Army doctors to detect surgically altered corneas, though lower degrees of refractive correction still can be difficult to detect using this instrument alone (Schallhorn et al., 1998). Computerized corneal topographers, also, will likely play an important role in military vision research since they will enable us to measure the optical properties of the human cornea in greater detail than has ever been possible before. Highly accurate corneal topography measurements are absolutely essential to any study of the complicated optical aberrations which follow refractive surgery, and this is the key to perfecting these techniques. One day topography guided lasers may be able to custom design individual corneas for "super-normal" vision (Wu, 1997). Superior optical correction of the eye also will allow the development of ultra-high resolution retinal photography, which will improve the diagnosis and management of diseases which affect the microscopic structure of the retina (Liang, Williams, and Miller, 1997).

Several technologies have been developed to measure precisely the surface topography of the cornea, but by far the most widely used instruments are known as computerized video-keratoscopes. Videokeratoscopes are being used clinically to diagnose subtle surface anomalies of the cornea. For example, videokeratoscopes are used routinely prior to refractive surgery to rule out the presence of a keratoconus, a degenerative condition which is an absolute contraindication to refractive surgery. Manufacturers generally claim that their instruments are capable of measuring the corneal surface to an accuracy of 0.1 D, and this is sufficient for current clinical applications. But, higher accuracy is necessary to compute the exact optical properties of the cornea.

Figure 3. Views of a 1-year post-PRK cornea under low magnification (left) and slit lamp illumination (right). Note: The faint ring visible in the left figure is associated with the iris contour and is not within the 6-mm radius where PRK was performed.

Keratometry - The predecessor of videokeratoscopy

Prior to computerized videokeratography, the only instrument available to most clinicians for measuring corneal surface shape was the keratometer. The keratometer estimates the central radius of curvature of the cornea in two principle meridians by optically measuring the local radius of curvature at four paracentral points. The local radii normally are converted to refractive power based on a paraxial power formula (Equation 1). Here the apical radius (r) is expressed in meters, and K is in diopters.

$$K = (0.3375) / r \qquad \text{Equation 1}$$

By the mid 1990s, computerized videokeratography had become available for widespread clinical use, and it represented a quantum leap beyond the keratometer in the amount of information it provided. These instruments sample 5-10 thousand points covering most of the corneal surface, and for each of these points, a local radius of curvature is estimated. Commonly, a keratometer-like definition for local radius, the *axial radius of curvature,* is used, and each radius value is converted into diopters using Equation 1. These data are displayed in a color "topographic" map. These axial curvature maps, which depict "K" (keratometer) readings across the cornea, became the clinical standard for corneal topographic mapping, in spite of the fact that the paraxial formula (Equation 1) does not correctly estimate surface refractive power except at the center of the cornea (Salmon and Horner, 1995; Roberts, 1994a; Mandell, 1992).

Importance of accurate surface elevation measurements

For most current clinical applications such as the detection of relative shape anomalies (e.g., keratoconus), consistent repeatability is more important than absolute measurement accuracy.

However, for advanced studies of corneal performance, absolute local surface elevation data are needed, and greater accuracy becomes critical. If these instruments can measure the surface elevation of a real cornea to micrometer (μm) accuracy, it will be possible to compute the corneal wavefront aberration function (Hemenger, Tomlinson, and Oliver, 1994), which is the key to understanding corneal optics.

During the 1990s, the two most popular corneal topographers, the EyeSys 2000 Corneal Analysis System and the Tomey TMS-1, used *spherically biased* algorithms to mathematically reconstruct the corneal topography from raw videokeratoscope data (Roberts, 1994b; Cohen et al., 1995), although better algorithms had been developed (Doss et al., 1981; Wang, Rice, and Klyce,1989; van Saarloos and Constable, 1991). In an effort to improve accuracy, another system, Alliance Medical's Keratron, incorporated an *aspheric* algorithm which eliminates many of the assumptions required by older machines. One recent study indicates that, indeed, their "arc-step" algorithm significantly improves accuracy (Tripoli et al., 1995). In late 1994, EyeSys Technologies redesigned their instruments and added side cameras to record the position of the corneal apex and an automatic focus mechanism to minimize operator error. In October 1996, software version 3.2 was released with an aspheric reconstruction algorithm designed to improve accuracy and eliminate problems associated with the previous spherically biased programs. The current version (4.0) includes new display options but uses the same corneal reconstruction algorithm as in version 3.2. The purpose of the investigation described here was to test whether the EyeSys 2000 Corneal Analysis System, with its aspheric reconstruction algorithm, is capable of measuring corneal topography to the level of accuracy required to compute the corneal wavefront aberration function. This preliminary study is necessary before the videokeratoscope can be used to study in detail the optical results of refractive surgery and prepare for better optical design of the cornea for optimal vision.

Available estimates of videokeratoscopy accuracy

Standard keratometer calibration uses spherical test surfaces such as steel ball bearings, and early studies of computerized videokeratoscope accuracy similarly tested these instruments with spherical surfaces and expressed results in diopters. First generation instruments had accuracies of ±0.25 D, which was similar to that expected for keratometery (Hannush et al., 1989; Heath et al., 1991). Current instruments claim to measure the corneal surface to an accuracy of 0.1 D (Bores Eye Institute, 1997).

Most manufacturers specify the accuracy of their instruments in diopters, but for the purposes of computing corneal optics, it is preferred to know surface elevation measurement error in terms of μm. In order to compare accuracy in diopters to accuracy in μm, dioptric and μm corneal data were calculated for a typical corneal profile represented by an ellipse with apical radius $r = 7.8$ and shape factor $p = 0.8$, where p is defined as $1-e^2$ (e = eccentricity). As shown in

Figure 4, these two parameters are related by a simple linear relationship (Equation 2), where 0.1 D error equals approximately 1.5 μm error at the edge of a 6.0-mm diameter cornel zone.

$$(\text{Error in } \mu\text{m}) \approx (14.6)(\text{Error in diopters}) \qquad \text{Equation 2}$$

Until recently, videokeratoscope algorithms assumed that local regions of the cornea could be represented by a series of spheres centered on the instrument's optical axis, and, as a result, these instruments had a strong spherical bias (Roberts, 1994a,b). Therefore, it was no surprise that they measured spherical surfaces accurately, but this was not necessarily an indication of accuracy on human eyes, since the cornea is an aspheric surface. For this reason, recent studies have tested videokeratoscope accuracy using ellipsoidal or other aspheric surfaces, and results usually are expressed in μm of elevation rather than diopters of power. Table 1 summarizes selected results from several studies. These results give a general indication of videokeratoscope accuracy. Two summary statistics are shown: 1) Root mean square (RMS) error across the entire measured surface and 2) accuracy at the edge of a 6.0-mm zone. A 6.0-mm diameter zone was selected since this is the normal maximum extent of the portion of the cornea which is relevant for vision and is the diameter of PRK and LASIK treatment zones. Error is defined as the measured surface elevation minus the known elevation of the surface at that point.

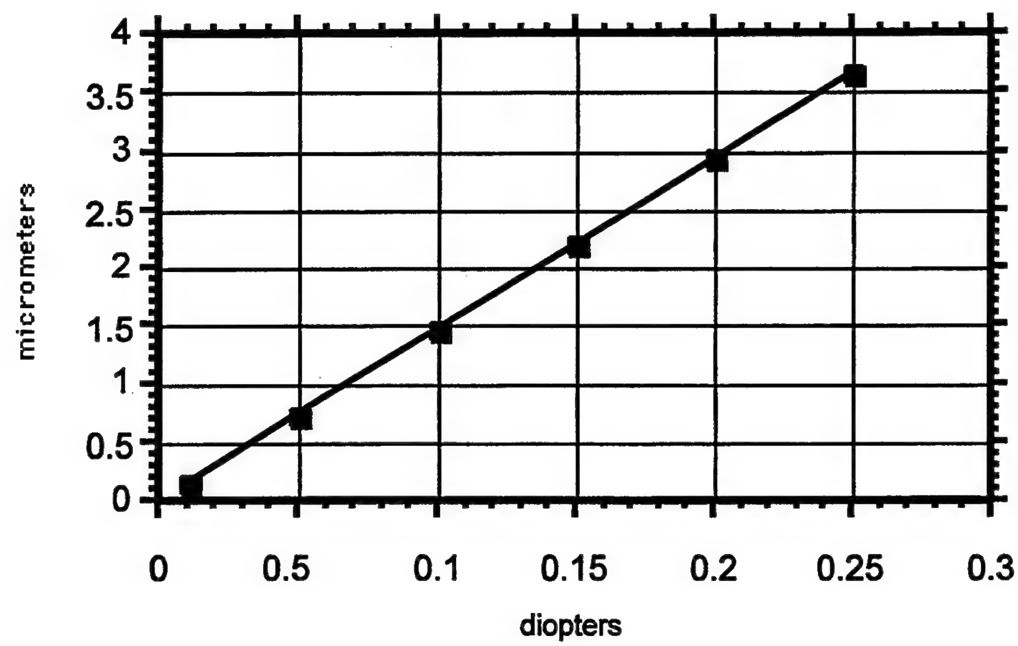


Figure 4. Comparison of two methods for videokeratoscope accuracy: Dioptric curvature and elevation in μm.

Table 1.
Videokeratoscope accuracy in measuring surface elevation of aspheres, according to several studies.

Study	Instrument (software version)	Test surface	RMS error (μm)	Maximum error (6-mm zone)
Applegate[a] et al. (1995)	TMS-1 (V1.41)	Ellipsoids	11.6 - 18.5	5 - 16
Applegate[b] et al. (1995)	TMS-1 (V1.41)	Elllipsoids	2.3 - 5.0	2 - 5
Douthwaite[c] (1995)	EyeSys (V2.00)	Ellipsoids	7 - 11	6 - 8
Cohen et al. (1995)	TMS-1 (V1.41)	Aspheres	8 - 28	4 - 8
Tripoli[d] et al. (1995)	Keratron	Aspheres	<1	0.1 - 0.25

[a] Default TMS algorithm
[b] Specially designed reconstruction algorithm
[c] RMS error estimated from results
[d] RMS error estimated from figures

Applegate et al. (1995) tested the Tomey TMS-1 using rotationally symmetric spheres, ellipsoids, and bicurves. They used two different algorithms to estimate the surface elevation of the test surfaces. In addition to the default instrument algorithm, they also processed the data using their own algorithm. Table 1, lines 1 and 2, summarizes results from this study for the ellipsoid test surfaces only. Line 1 shows the accuracy when the default TMS program was used. Line 2 shows that higher accuracy was obtained when elevations were computed using the program written by Applegate et al. (1995). The TMS-1 is now an old machine, having been replaced by the TMS-2, but this shows that, with a better algorithm, even the older instrument had the potential to measure surface elevation of ellipsoids with an overall and 6-mm zone edge accuracy of 5 μm or better.

Douthwaite (1995) tested a previous generation EyeSys Corneal Analysis System with 24 ellipsoids of varying apical radii (r_0) and shape factors (p) to represent a range of normal corneal surfaces. Before his finding could be compared with other studies, we had to convert his results by the following procedure. The EyeSys instrument outputs data files containing the axial radii (r_a) and radial distance from the center (y) for each sampled point. Equation 3 shows that for an ellipse, a linear relationship exists such that, if r_a^2 is plotted as a function of y^2, the y-intercept is equal to the apical radius squared (r_0^2) and the slope is (1-p).

$$r_a^2 = r_0^2 + (1-p)y^2 \qquad \text{Equation 3}$$

Using these relationships, Douthwaite (1995) computed an apical radius and shape factor for each test surface, and these were plotted against the known values to evaluate the instrument's accuracy. He developed the following formula (Equation 4) which showed the relationship between the true apical radius (r_0) and the radius (r_E) derived from the EyeSys measurement.

$$r_E = 1.01\, r_0 + 0.036 \qquad \text{Equation 4}$$

Similarly, the relationship (Equation 5) between the true shape factor (p) and the EyeSys derived shape factor (p_E) was:

$$p_E = 0.839\, p + 0.185 \qquad \text{Equation 5}$$

Using Douthwaite's formulae, we computed the expected surface elevation error at 0.25-mm intervals from a 0- to 10.0-mm diameter zone for various ellipses. This allowed us to express Douthwaite's accuracy results in terms of RMS error and the 6-mm zone edge error for comparison with the other studies shown in Table 1. The overall RMS accuracy was 7-11 μm, and 6-mm zone edge error was 6-8 μm, depending on the exact apical radius and p value.

Cohen et al. (1995) tested the TMS-1 using the default TMS program for surface elevation on four test surfaces. Two of the surfaces were constructed with a combined elliptical/parabolic profile while the other two surfaces were non-conic aspherics. His RMS errors (8-28 μm) were similar to those measured by Applegate et al. (1995) using the default TMS-1 program; the 6.0-mm zone edge error (4-8 μm) was similar to the Douthwaite (1995) results.

Tripoli et al. (1995) repeated the study of Cohen et al. (1995) using a different instrument, Alliance Medical's Keratron, which is claimed to use a more accurate surface reconstruction method (the arc-step algorithm) than their competitors. RMS errors were not reported, but from the figures showing error at different radial distances, it is clear that overall error within a 9-mm diameter was less than 1 μm. This is entered in Table 1 under the RMS column. For a 6.0-mm zone, edge accuracy was 0.10 - 0.25 μm.

These studies show that older videokeratoscopes, using older software, would be able to measure the surface elevation of ellipsoids to within 10-30 μm; with newer software, accuracy with the same instruments improves to 2-5 μm or better. The corneal wavefront aberration function, one of the best descriptors of optical aberrations (Williams and Becklund, 1989), can be estimated directly from surface topography, and a 2-5-μm surface elevation error translates to a wavefront aberration error of 0.7-1.7 μm (Howland, Buettner, and Applegate, 1994; Applegate et al., 1995) or 1.0-2.67 wavelengths ($\lambda = 0.633\ \mu$m). Since maximum wavefront aberrations for the human eye are in the 2-10 wavelength range (Charman, 1991), it is desirable to measure corneal topography to single μm accuracy, or better, when computing corneal optics. Tripoli et al. (1995) indicated that the Keratron, one of the newest videokeratoscopes, is capable of this accuracy under ideal conditions.

Figure 5. The EyeSys Technologies Corneal Analysis 2000 system.

Methods

Instrumentation

The EyeSys Technologies Corneal Analysis 2000 system (Figure 5) consists of three cameras (two side-mounted alignment cameras and one digitizing video camera located at the center of an illuminated pattern of concentric rings) and a computer system. The center camera images the pattern of the rings which are reflected from the cornea. When the image is acquired, it is digitized, and a proprietary algorithm computes the axial radius of curvature at each point. Radii are converted to diopters as described previously (Equation 1), and a color topographic map of the cornea is displayed. Figure 6 shows a corneal topography map for the same post-PRK cornea shown in Figure 3.

Test surfaces

Six rotationally symmetric apherical test surfaces were measured to assess instrument accuracy. The black polymethymethacrylate (PMMA) surfaces were manufactured by Sterling International Technologies which guarantees the surfaces to within 1.0 μm over a 10-mm diameter zone. Samples of the surfaces were verified by the manufacturer using a Rank Taylor Hobson Talysurf, a device which makes stylus measurements to a resolution of better than 0.1 μm. The manufacturer claims that these surfaces are therefore accurate to 0.1 μm, although they guarantee only 1.0 μm accuracy. A representative test surface is shown in Figure 7.

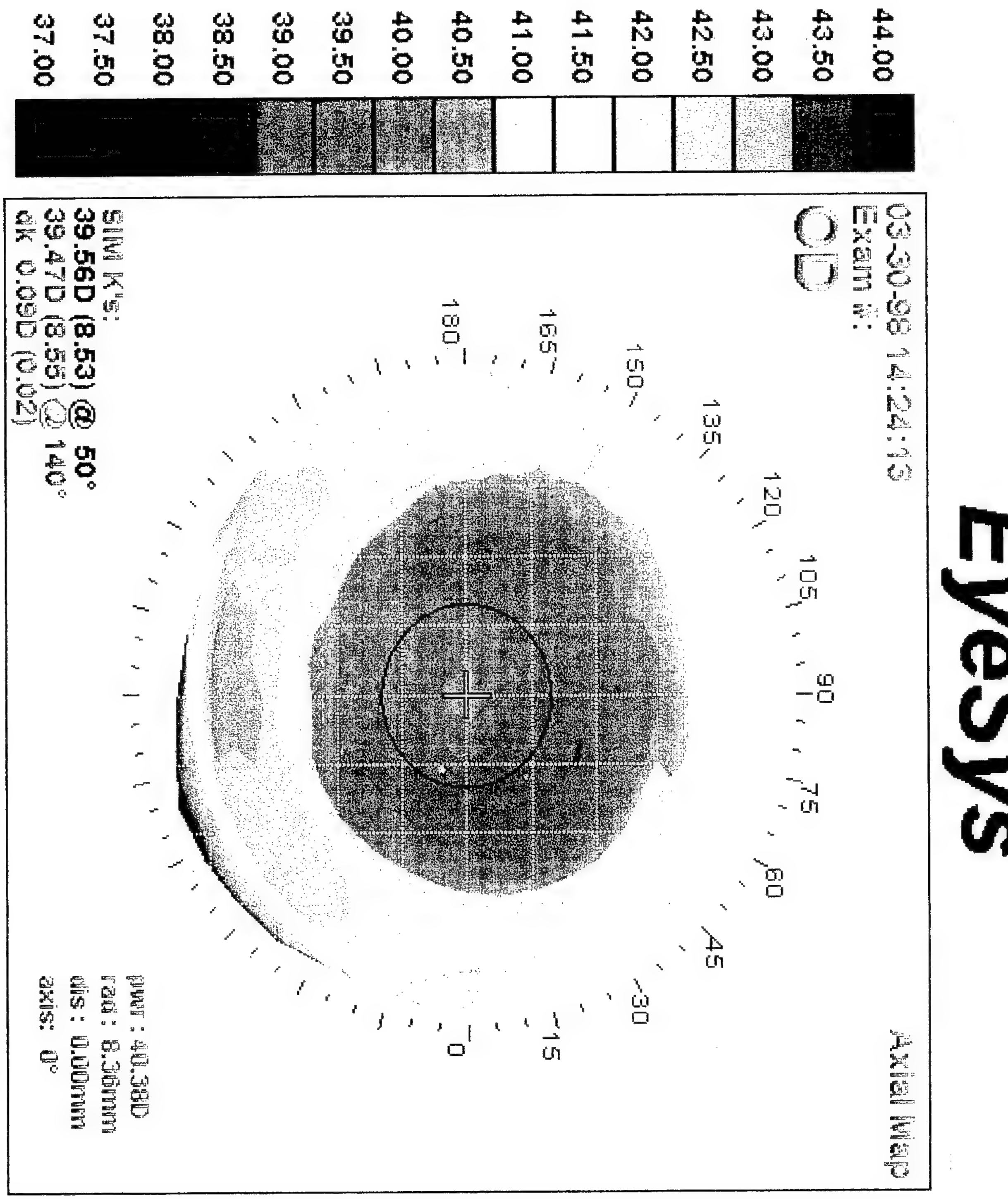


Figure 6. A corneal topography map for the same post-PRK cornea shown in Figure 3. The central zone has been flattened to provide correction for myopia while the periphery remains unaltered.

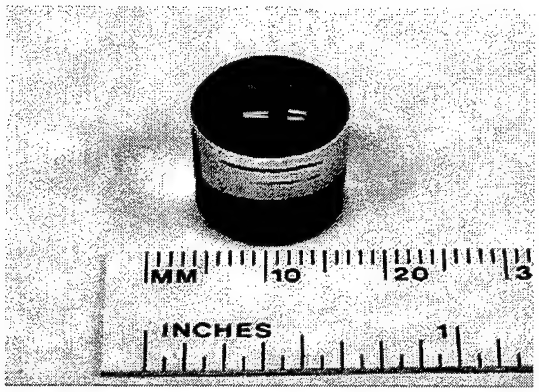


Figure 7. Representative test surface.

Four of the six surfaces were prolate in form, i.e., flattens peripherally. These were designed to represent the range of shapes expected for most normal corneas. One surface has spherical profile, and one other surface was an oblate in form, i.e., steepens peripherally. These were designed to generally represent post refractive surgery corneas, though a small number of normal corneas are also oblate in shape (Keiley, Smith, and Carney, 1982; Eghbali, Yeung, and Maloney, 1995). Table 2 summarizes parameters for the test surfaces.

Table 2.
Parameters for the test surfaces used in this study.

Surface #	Apical radius (mm)	Shape factor (p)	Eccentricity (e)	Description
1	7.8	1	0	sphere
2	7.8	.7	.55	average cornea
3	7.8	.5	.71	more aspheric
4	7.8	1.3	NA	oblate ellipse
5	7.3	.7	.55	steep cornea
6	8.3	.7	.55	flat cornea

Procedure

Prior to making measurements, the EyeSys 2000 system was calibrated as specified in the operator's manual. Each test surface was mounted in a holding device which allowed tilt and position adjustments so the surface could be precisely centered and aligned coaxially with the instrument's optic axis. An initial image was taken and the color map was evaluated for

centration and alignment. Fine adjustments were made, and these steps were repeated until optimal alignment was achieved based upon a criteria of minimal surface toricity (astigmatism), correct apical radius, and map symmetry. Eighteen keratographs then were taken of each surface. One example of the corneal topography maps for a test surface is shown in Figure 8.

Most videokeratoscope maps, including the examples shown in Figures 6 and 8, present the corneal surface in terms of local dioptric data, but we needed to know the surface elevation in µm. A utility program provided by EyeSys converted the standard curvature data into elevation data. The mean elevations measured for each test surface were taken as the mean data from eighteen images of each surface.

Data analysis

From the specified apical radius and shape factor for each test surface, it was possible to compute the expected surface elevations at each point on the surfaces, and the measured elevations were compared with these to determine instrument error. Therefore, error was defined as measured minus known elevation for each position. The keratoscope image (keratograph) contains 18 concentric rings, each of which is used to compute the corneal elevation at 18 distances from the center. Within each ring, 360 evenly spaced measurements were made. Therefore, the keratoscope samples the cornea at 6,480 points on a polar grid composed of 360 spokes and 18 rings. Taking advantage of the rotational symmetry for each surface, a mean surface elevation for each ring then was computed to show how error changed as a function of distance from the center. The result of this analysis was a mean surface elevation error at 18 distances beginning with a point approximately 0.25 mm from the center to approximately 4.5 mm from the center. This covers an approximately 9.0-mm diameter zone of the model corneas. From the 18 elevation error values, an RMS error was computed to represent a mean overall measurement error for each surface. In addition, the elevation error at the 12th ring, which was approximately 3.0 mm from the center, also was noted to evaluate the maximum error expected within a 6.0-mm corneal zone.

Theoretically, to compute optical aberrations of the cornea, surface topography is expressed best as surface elevation in microns, but because axial curvature in diopters is so commonly used, error also was expressed in diopters. The instrument measured the axial curvature in diopters for each sampled point, but true expected value had to be computed based on the known apical radius (r_o) and shape factor (p) for each surface. Equation 6 was used to compute the axial radius of curvature (r_a) at each distance from the center for which measurements were obtained, and the radii were converted to diopters according to Equation 1. Dioptric error was defined as the difference between the measured and known values for each position.

$$r_a = \mathrm{sqrt}(r_o^2 + (1\text{-}p)y^2) \qquad \text{Equation 6}$$

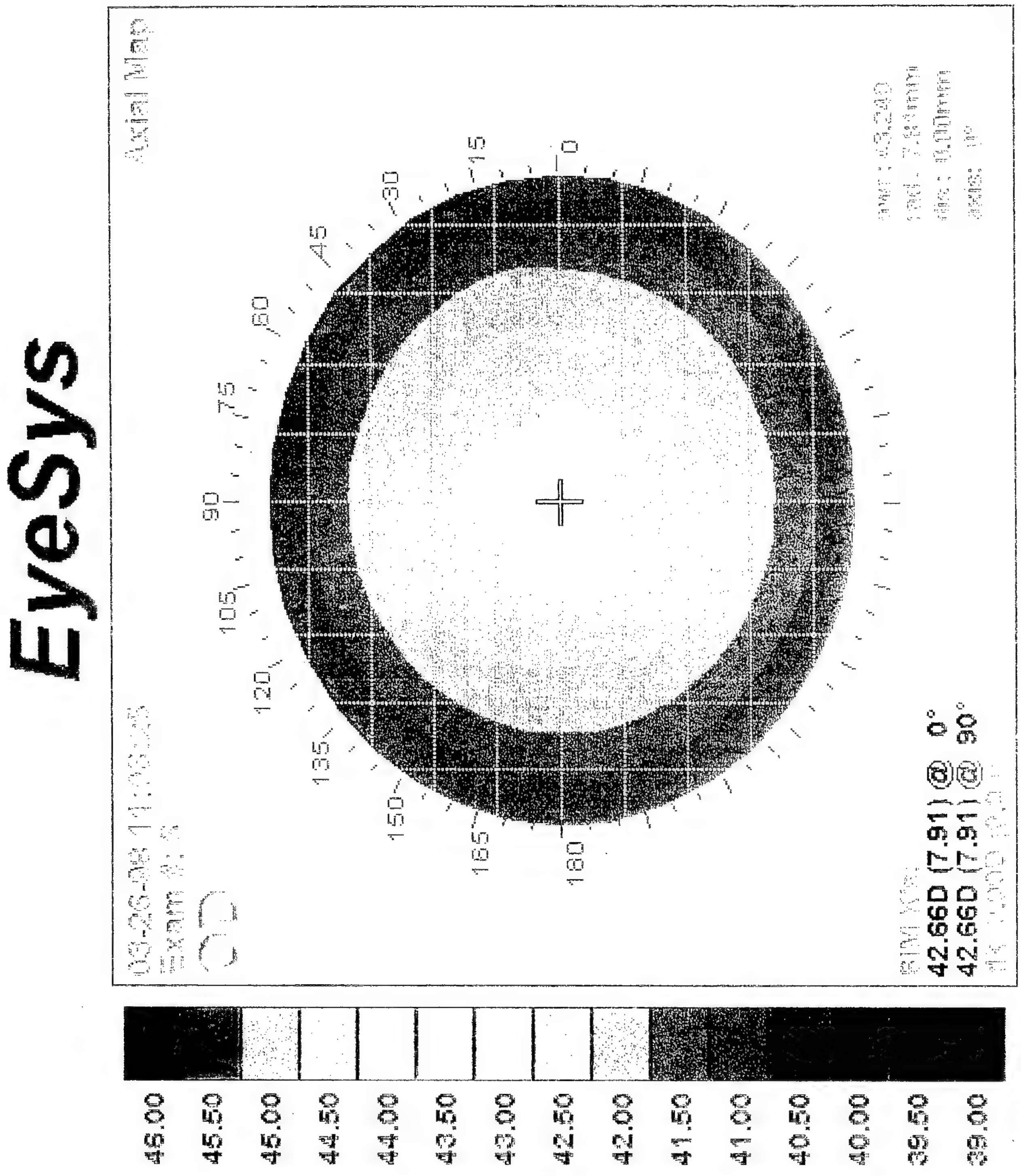


Figure 8. Example of a corneal topography map for a test surface.

Results

The RMS surface elevation measurement error and measured zone diameter for each surface are listed in Table 3. The best results were for the oblate ellipsoid (r = 7.8 / p = 1.3), with an RMS error of 2.0 μm. The range of RMS error for the other surfaces was approximately 4-9 μm. Four of the surfaces had the same apical radius of 7.8 mm but differed in p values (p = 0.5, 0.7, 1.0, and 1.3). Among them, accuracy was better for surfaces with higher p values. Three surfaces had the same p value (0.7) but differed in their apical radii (7.3, 7.8, and 8.3). RMS error for each of these three surfaces was 7.3, 7.2, and 7.0 μm, respectively. Depending on the surface, an 8.6- to 10.0-mm "corneal" zone was sampled.

Table 3.
RMS surface elevation measurement error for six model corneas.

Parameter (r/p)	RMS error (μm)	Measured zone (mm)
7.8 / 1.3	2.0	8.6
7.8 / 1.0	4.3	9.0
7.8 / 0.7	7.2	9.4
7.8 / 0.5	8.8	9.8
8.3 / 0.7	7.0	10.0
7.3 / 0.7	7.3	8.8

Table 4 shows the mean surface elevation measurement error for the 12^{th} ring of each surface, which was located at approximately 3 mm from the center. The distance to the 12^{th} ring varied slightly from surface to surface depending on its particular apical radius and p value. The negative error for each surface indicates that the EyeSys underestimated the surface elevations. As with the RMS values described above, accuracy was best for the oblate ellipsoid (r = 7.8 / p = 1.3), with an error of -2.1 μm. The range of error for the remaining surfaces was approximately - 4 to - 6 μm. Where the apical radius was constant, surfaces with greater p values had smaller errors (top four rows). Three surfaces with the same p value (0.7) showed decreasing errors with increasing apical radius, but all errors were within the -5 to -6 μm range.

For many users of videokeratoscopes and corneal topography maps, accuracy in diopters is more familiar, so Table 5 expresses the RMS and 12^{th} ring errors in diopters rather than in µm. Both RMS and the 12^{th} ring dioptric errors were in the general range of 0.25 D. As noted before, accuracy was slightly better for the oblate ellipsoid (r = 7.8/ p = 1.3) and the result was worst for the steepest surface (r = 7.3). The negative values for 12^{th} ring error indicate that the instrument underestimated the dioptric curvatures.

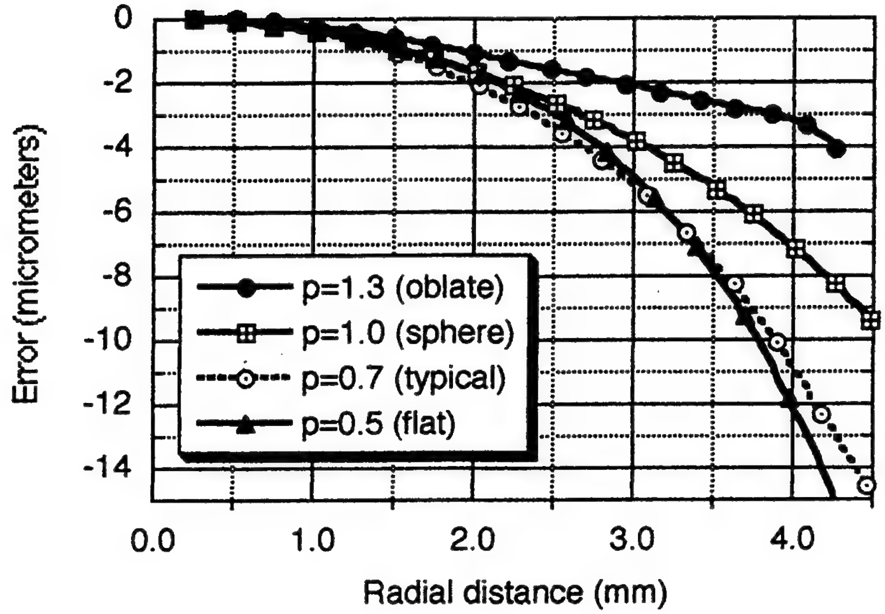
Table 4.
Surface elevation measurement error (μm) at the 12^{th} ring for six model corneas.

Surface parameter (r/p)	Elevation error	Radial distance from center (mm)
7.8 / 1.3	-2.1	3.0
7.8 / 1.0	-3.8	3.0
7.8 / 0.7	-5.5	3.1
7.8 / 0.5	-5.5	3.1
8.3 / 0.7	-5.0	3.3
7.3 / 0.7	-5.8	2.9

Table 5.
RMS and 12^{th} ring dioptric error for six model corneas.

Parameter (r/p)	RMS error (D)	Error at the 12^{th} ring
7.8 / 1.3	0.19	-0.18
7.8 / 1.0	0.25	-0.23
7.8 / 0.7	0.29	-0.29
7.8 / 0.5	0.27	-0.29
8.3 / 0.7	0.23	-0.27
7.3 / 0.7	0.37	-0.34

Tables 3-5 give single values which summarize accuracy for each surface, but the accuracy trend as a function of radial distance from the center is shown in Figures 9 and 10. Figure 9 shows the surface elevation error in µm for the surfaces which had identical aprical radii (7.8 mm) but differed in p value. The bottom plot shows the trend for three surfaces which had a constant p value but differed in apical radii. All curves show that measurement error increased monotonicly from center to periphery. As was noted above, error was smaller for the oblate ellipsoid (p = 1.3), and when apical radius is constant, error increases with lower p value,



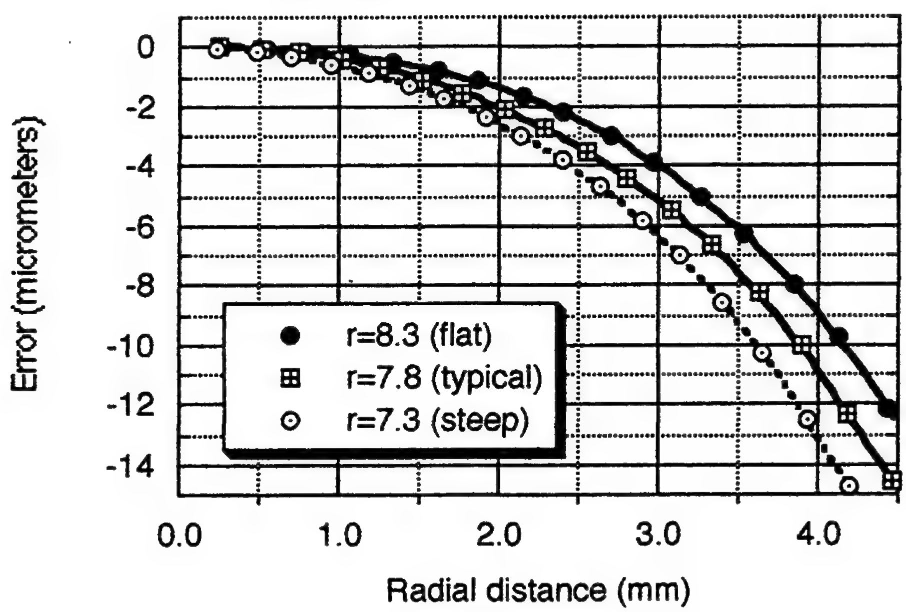
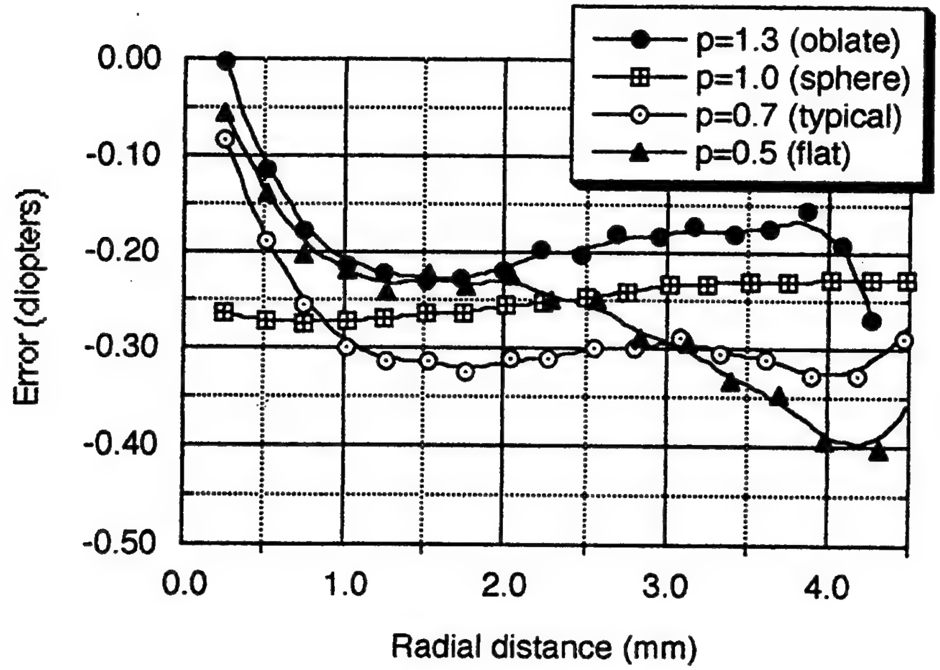


Figure 9. Surface elevation error as a function of radial distance from the center. Top: Four surfaces with the same apical radius (r = 7.8 mm) but different shape factors (p). Bottom: Three surfaces with the same shape factor (p = 0.7) but different apical radii (r).



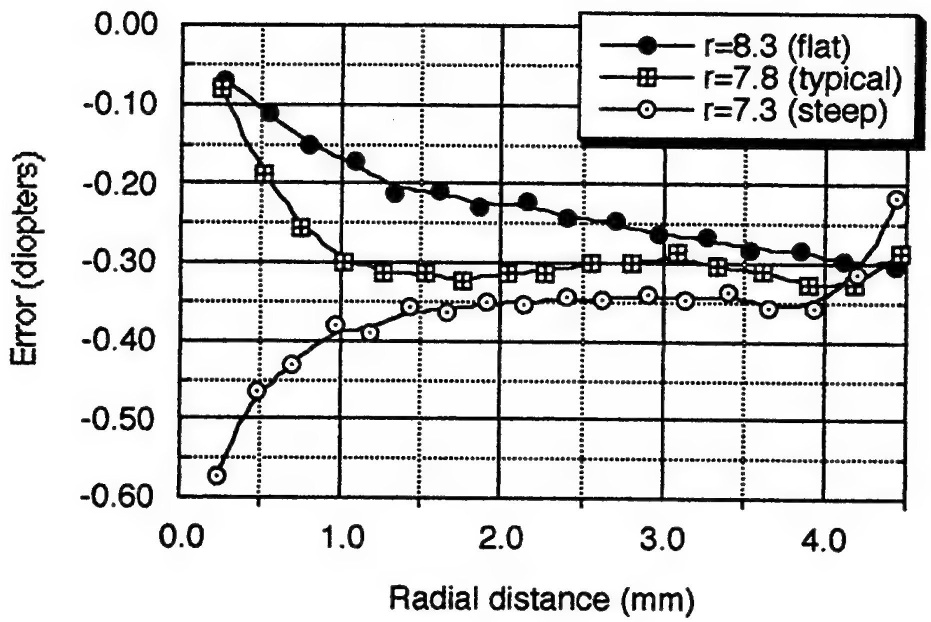


Figure 10. Axial curvature error as a function of radial distance from the center. Top: Four surfaces with the same apical radius (r = 7.8 mm) but different shape factors (p). Bottom: Three surfaces with the same shape factor (p = 0.7) but different apical radii (r).

i.e., for surfaces which show greater flattening peripherally. The lower plot shows that, for a given p value, greater error is seen in surfaces with shorter apical radii, i.e., steeper surfaces. Figure 10 shows error for the corresponding surfaces expressed in diopters. Generally, dioptric error was very small near the center of the surfaces, increased to the 0.2 - 0.3 D range at 1 mm from the center, then remained relatively constant peripherally. Some exceptions were noted. The spherical surface (p = 1.0) showed a fairly constant error of approximately 0.25 D across the surface. The steepest surface (r = 7.3 mm) showed unusually large error centrally (-0.57 D), which quickly decreased peripherally.

Discussion

The primary purpose of this study was to determine if the EyeSys Corneal Analysis System could measure the topographic elevation of cornea-like test surfaces accurately enough to permit detailed studies of corneal optics. For this purpose, elevation measurement accuracy should be better than 1.0 µm. Our results showed the EyeSys system was not able to achieve this level of accuracy for any of the test surfaces. Depending on the surface, accuracies expressed as RMS or 12th ring errors were in the 2 to 9 and -2 to -6-µm ranges, respectively.

Our findings are generally similar to the accuracy reported by Applegate et al. (1995) for the TMS-1 topographer which used the improved reconstruction algorithm, and this is better than the accuracy reported for older instruments using older algorithms. This suggests that the aspheric algorithm used by the current EyeSys system is an improvement over previous versions, but is not accurate enough for corneal optics studies in which sub-µm accuracy is needed. When examining Figure 9, it is clear that the error is systematic and varies as a function of distance from the center, apical radius, and p value. Taking these factors into account, it should be possible to compensate for and eliminate most of the systematic error. This method was used in one recent study (Salmon and Thibos, 1997) to improve surface elevation accuracy using the EyeSys system to a 0.2-µm, or better, accuracy for ellipsoidal test surfaces. Since Tripoli et al. (1995) reported 0.25-µm accuracy for the Keratron, it appears that, with the appropriate calibration and reconstruction software, computerized videokeratoscopes should be capable of measuring the surface of the cornea to sub-µm accuracy. Figure 10 shows a nearly constant axial curvature error of -0.25 D, and this also suggests a systematic error in the EyeSys algorithm, which should be easily corrected.

All studies with model corneas give best case accuracy estimates. However, greater variants and error can be expected with real eyes due to ocular movements, more difficult focusing, and fluctuations in the tear film caused by blinking and evaporation.

The problem of asymmetric surfaces

Because the keratoscope mires are concentric rings with no spokes or cues to mark meridional position, current commercial reconstruction algorithms must assume that every point

on the data image has been reflected from a point on the target which was in the same radial meridian (Applegate and Howland, 1995). This assumption simplifies computations by treating each radial meridian as one slice out of a rotationally symmetric surface. In other words, they ignore any possible oblique ray reflections (Klein, 1997a) at the corneal surface. Current video-keratoscopes use this assumption in reconstructing surfaces, so for rotationally symmetric surfaces, such as our model corneas, these algorithms should perform well. Unfortunately, human corneas are almost never so symmetric. The most familiar example of corneal asymmetry is surface toricity which causes astigmatism. Therefore, we might expect accuracy on real human corneas to be somewhat worse than indicated in this study. Greivenkamp et al. (1996) tested three older videokeratoscopes for accuracy in measuring the surface elevation of toric surfaces designed to model 0-7 D of corneal astigmatism. Results are summarized in Table 6. For 1 D of astigmatism, the EyeSys topographer using software version 2.1 was still accurate to 0.7 μm (RMS), while the TMS-1 (version 1.41) and Visioptic EH-270 (version 3.0) were accurate to 3.7 and 1.9 μm, respectively. For higher degrees of toricity, accuracy with the TMS and EH-270 improved slightly while the EyeSys was worse. For all three instruments, accuracy for the most extremely toric (7 D) surface was better than 10 μm, which is approximately the same magnitude of error reported for the TMS and EyeSys for rotationally symmetric surfaces (Table 1).

Klein (1997b) investigated the magnitude of videokeratoscope errors in measuring asymmetric surfaces of a variety of shapes. He found that for toric ellipsoids the dioptric error was very small and could be estimated using Equation 7,

$$\text{error} = (C/2)^2 / 2M \qquad \text{Equation 7}$$

where C is the corneal astigmatism, and M is the mean apical curvature of the cornea, both expressed in diopters. For a typical average cornea with mean spherical power of 43 D and 1.00 D of astigmatism, the maximum expected error is 0.003 D, which according to Equation 2 equates to a 0.04 μm elevation error. Even for an extreme 4.00 D value of corneal astigmatism, the dioptric and elevation errors are only 0.05 D and 0.70 μm, respectively.

Table 6.
RMS error (μm) for toric test surface with three older videokeratoscopes (8-mm "corneal" zone). (Greivenkamp et al., 1996)

Toricity (D)	TMS-1 (v 1.41)	EyeSys (v 2.01)	Visioptic EH-270
0	0.7	0.6	0.8
1	3.7	0.7	1.9
2	2.5	5.3	1.2
3	1.7	7.5	1.5
7	4.2	9.7	2.4

For more distorted corneas, such as in keratoconus, the error can be much larger, and Klein (1997a) developed an arc-step algorithm which eliminates the skew ray error. Hilmantel et al. (1997) modeled corneal asymmetry by using tilted ellipsoids and found that even with an extreme 15 degrees of tilt, RMS error with the TMS-1 (using Applegate's reconstruction algorithm) was 2.7 μm. These studies indicate that for small degrees of asymmetry, such as the toricity seen in most normal corneas, accuracy is not much different from that found for rotationally symmetric surfaces.

Conclusions

This study tested the accuracy of one widely used videokeratoscope, the EyeSys Corneal Analysis System using PMMA ellipsoidal surfaces designed to model a range of corneal shapes. Without modification, the EyeSys videokeratoscope cannot measure corneal surface topography at the level of accuracy required for detailed studies of corneal optics. However, systematic instrument error can be corrected, and, if compensated, the basic hardware seems to be capable of the sub-μm accuracy required for these studies. Though these instruments appear to be adequate for most current applications, vision scientists cannot assume that their topographical data are sufficiently accurate for the more rigorous demands of corneal optics research. All such studies should first verify instrument accuracy using aspheric test surfaces, as was done in this study, and appropriate correction factors should be computed to optimize accuracy. Hopefully, manufacturers will improve instrument software to consistently deliver the higher accuracy necessary for future studies of corneal optics.

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Appendix.
List of manufacturers

Visioptic, Inc.
3300 South Gessner
Houston, TX 77063

Alliance Medical Marketing, Inc.
3948 South Third Street #282
Jacksonville Beach, FL 32250

EyeSys Technologies, Inc.
3 Morgan
Irvine, CA 82718

Rank Taylor Hobson
Suite 350
2100 Golf Road
Rolling Meadows, IL 60008

Sterling International Technologies
Crosspointe at Sabal, Suite 150
3102 Cherry Palm Drive
Tampa, FL 33619

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